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Apparent Tropospheric Response to MeV-GeV Particle Flux Variations: A Connection Via Electrofreezing of Supercooled Water in High-Level Clouds?

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The ionization production by MeV-GeV particles (mostly galactic cosmic rays) in the lower atmosphere has-well defined variations on a day-to-day time scale related to solar activity, and on the decadal time scale related to the sunspot cycle. New results based on an analysis of 33 years of northern hemisphere meteorological data show clear correlations of winter cyclone intensity (measured as the changes in the area in which vorticity is above a certain threshold) with day-to-day changes in the cosmic ray flux. Similar correlations are also present between winter cyclone intensity, the related storm track latitude shifts, and cosmic ray flux changes on the decadal time scale. These point to a mechanism in which atmospheric electrical processes affect tropospheric thermodynamics, with a requirement for energy amplification by a factor of about 10^7 and a time scale of hours. A process is hypothesized in which ionization affects the nucleation and/or growth rate of ice crystals in high-level clouds by enhancing the rate of freezing of thermodynamically unstable supercooled water droplets which are known to be present at the tops of high clouds. The electrofreezing increases the flux of ice crystals that can glaciate midlevel clouds. In warm core winter cyclones the consequent release of latent heat intensifies convection and extracts energy from the baroclinic instability to further intensify the cyclone. As a result, the general circulation in winter is affected in a way consistent with observed variations on the interannual/decadal time scale. The effects on particle concentration and size distributions in high-level clouds may also influence circulation via radiative forcing.

INTRODUCTION

The apparent meteorological and climate response to solar variability has been a controversial subject in scientific literature for the past two centuries. More than a thousand papers on the topic have appeared. Bibliographies have been given in the Solar-Terrestrial Physics and Meteorology Working Documents I-III (SCOSTEP, 1975, 1977, 1979]. Evidence for the apparent responses have been reviewed by *Herman and Goldberg* [1978*a*], the National Research Council [1982] panel, and *Taylor* [1986]. A series of papers by *Labitzke* [1987], *Labitzke and van Loon* [1988, 1989], and *van Loon and Labitzke* [1988] show that the statistical significance of apparent responses of stratospheric and tropospheric temperature and dynamics to the 11-year solar cycle is greatly increased when the data are stratified by the direction (quasi-biennial oscillation phase, or QBO phase) of equatorial stratospheric winds. Similar variations with solar cycle and QBO phase have been found for atmospheric electric potential gradient by *Märcz* [1990] and for total ozone by *Varotsos* [1989].

There are three agents that have been considered for forcing of solar variability effects on the atmosphere. The first is changes in total solar irradiance, providing a variable heat input to the surface, as originally suggested by *Herschel* [1801]. The decadal and short-term variations have recently been measured to be about 0.1% [*Schatten*, 1988], and their effects have been modeled and have been shown to be insignificant (less than 0.1°C) on this time scale [*Wigley and Raper*, 1990]. However, larger variations in total irradiance may exist on the centennial time scale that could force longer-term climate variations [*Eddy*, 1977; *Reid*, 1990].

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The second suggested forcing agent is variations in solar ultraviolet flux, with the hypothesis that changes in tropospheric dynamics are produced through the intermediate process of changes in the dynamics of the upper stratosphere, where the UV flux is absorbed. Attempts to evaluate the amount of such dynamical coupling have been made by *Geller and Alpert* [1980], *Dameris and Ebel* [1989], *Hood and Jirikowic* [1990], and *Kodera et al* [1990]. The UV variations have time scales predominantly that of the 11-year solar cycle and the 27-day solar rotation [*Donnelly et al.*, 1986; *Barth et al.*, 1990]. Since the UV flux is absorbed only in the middle stratosphere and above, the time scale for any tropospheric response would have to be convoluted with the time scale for the stratospheric response and for propagation of an amplifying and coupling process from the stratosphere to the troposphere. Such considerations suggest that while UV forcing is of interest for possible tropospheric response on the range of time scales from decadal/interannual down to that of the solar rotation, it is not a strong candidate to explain apparent tropospheric responses to solar activity (and particularly to variations in the solar wind) on the time scale of a day or two [*Holton*, 1982].

The third suggested forcing agent is the flux of MeV-GeV particles that is essentially the only source of atmospheric ionization in the stratosphere and troposphere down to about 2 km above the surface [*Ney*, 1959; *Dickinson*, 1975]. (Below 2 km, radon becomes a significant source, and above 60 km, solar Lyman alpha and X rays become significant.) The MeV-GeV particles are almost entirely cosmic rays from galactic sources, occasionally supplemented by solar particles from flares. The flux is modulated by changes in the solar wind which, as the outward extension of the solar corona, changes with solar activity. The flux in the range of about 10^2 to 10^3 MeV shows clear variations on the centennial, decadal, solar rotation and day-to-day time scales, with the percentage changes being considerably greater than those for total solar irradiance, and greater than those for irradiance changes of the

UV absorbed in the stratosphere. (On the decadal time scale the MeV-GeV flux varies by several tens of percent, while the UV variation at 200 nm is about 10%, according to *Lean* [1989]. However, in absolute terms, the variation in energy flux for the MeV-GeV particles of about 10^{-3} ergs cm^{-2} s^{-1} is very much smaller than the 10^{2} erg cm^{-2} s^{-1} of varying solar UV absorbed in the upper stratosphere [*Lean*, 1989].

There have been many reports of apparent tropospheric responses to magnetic storms [e.g., *McDonald and Roberts*, 1960; *Roberts and Olsen*, 1973; *Stolov and Shapiro*, 1974; and *Olsen et al.*, 1975]. Effects were found beginning on the day of storm onset, and lasting 4 or more days. Most large magnetic storms are preceded by a solar flare and a coronal mass ejection, which travels to the Earth as a high-speed plasma stream. Its arrival is coincident with the onset of the magnetic storm and also a sudden decrease of galactic cosmic ray flux known as a Forbush decrease. Thus apparent responses to magnetic activity can also be regarded as apparent responses to MeV-GeV flux changes. The amplitude of the Forbush decrease is usually several percent for several days, occasionally more than 10 percent. *Schuurmans and Oort* [1969] reported apparent responses to flares, and *Tinsley et al.* [1989], *Brown* [1989], and *Tinsley* [1990*a*] reported apparent responses to both the arrival of high-speed plasma streams and to Forbush decreases.

In their studies suggesting a connection between short-term solar variability and intensification of cyclones in the Gulf of Alaska, *McDonald and Roberts* [1960] and *Roberts and Olsen* [1973] speculated that a mechanism might involve stratospheric ionization changes, produced by solar particle precipitation, affecting clouds. *Dickinson* [1975] suggested that changes in cosmic ray fluxes and therefore in stratospheric ionization might affect cloud condensation nuclei and thus affect radiative forcing by high-level clouds. *Herman and Goldberg* [1978*b*] and *Markson and Muir* [1980] speculated that changes in conductivity above thunderstorms might affect cloud electrification and thunderstorm thermodynamics. *Lethbridge* [1990] showed correlations of thunderstorm activity with cosmic ray flux changes, and she speculated that interaction of ionization with meteoric dust acting as condensation nuclei might be important.

Figure 1 is an illustration on the decadal/interannual time scale of correlation of galactic cosmic ray flux and tropospheric dynamics. The top panel represents surface neutron monitor count rates from Climax, Colorado [*National Geophysical Data Center* (NGDC), 1989], which shows a 15% to 20% modulation in the flux of about 1 GeV in the lower atmosphere over the 11-year solar cycle, anticorrelated with the sunspot number, which is shown in the second panel from the top. Also shown in the top panel is the variation in cosmic ray flux (above about 500 MeV) in the polar stratosphere, which has an amplitude of about 40%. These data are from daily Soviet Arctic and Antarctic balloon measurements [*Lebedev Institute*, 1968-1973; *IZMIRAN*, 1972-1989] supplemented by Thule balloon measurements [*Neher*, 1971]. The third panel shows changes in the mean latitude of winter storm tracks in the north Atlantic crossing 5°E longitude for latitudes above 50°N [*Brown and John*, 1979] (updated by *John* [1989, 1990]). The smoothed latitude deviations show a good correlation with sunspot number for six cycles since 1920, and this should be enough to satisfy the criterion of *Pittock* [1978] for confidence that the correlation is not the accidental coincidence of decadal scale variations but arises

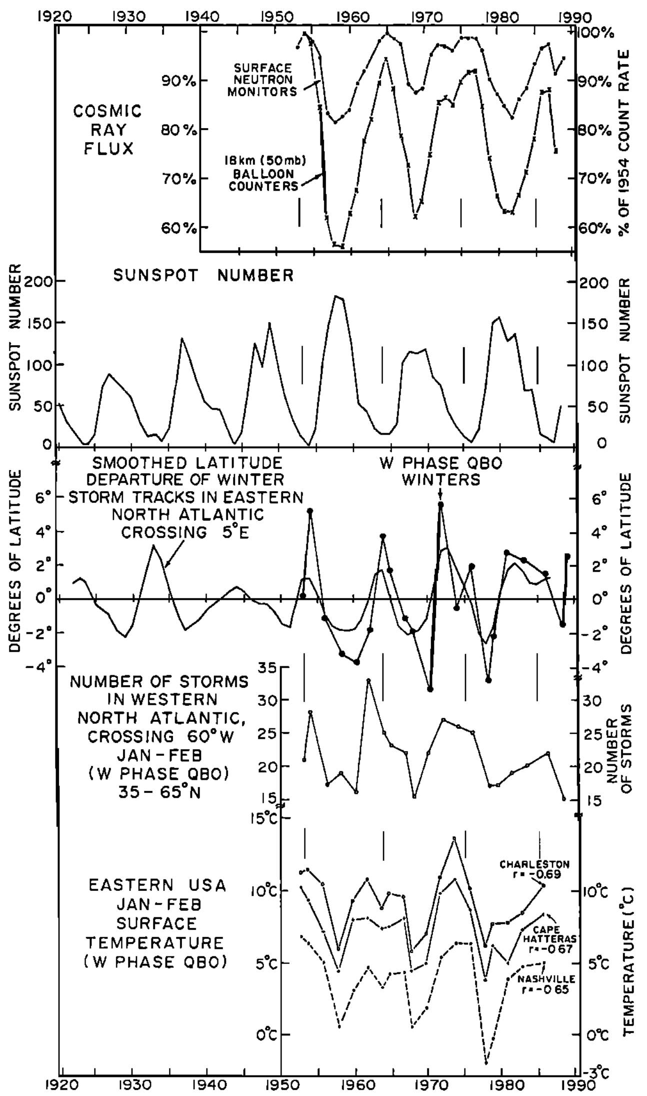

Fig. 1. Correlation of solar and cosmic ray variability with tropospheric dynamics and temperature on the decadal/interannual time scale. The cosmic ray flux is from the Climax neutron monitor and daily Soviet Arctic and Antarctic balloon measurements supplemented by Thule measurements. The storm track latitudes are smoothed values for winter storms crossing 5°E above 50°N latitude, with unsmoothed values for QBO west phase winters superimposed. The storm frequencies are for those crossing 60°W between 35°N and 65°N for QBO west phase. Surface temperatures in eastern North America are also for QBO west phase winters. See text for details and sources.

from a physical connection. The deviations in storm track latitudes for winters in the west phase of the quasi-biennial oscillation (QBO) of equatorial stratospheric winds were shown by *Tinsley* [1988] to have a stronger correlation with the solar cycle than for east phase winters, and the updated results from *John* [1990] from 1953-1989 are shown (unsmoothed) in the third panel.

The frequency of winter storms in the western north Atlantic correlates well with cosmic ray flux for QBO west phase winters from the time QBO data became available in 1952 [*Labitzke and van Loon*, 1989; *John*, 1990] and is shown in the fourth panel. As noted by *Tinsley et al.* [1989], a downstream latitude shift of the storm tracks is a dynamical consequence of the change in storm frequency (or equivalently, changes in the intensity of individual storms). We note that the storm frequency varies by several tens of percent from solar maximum to solar minimum, and this can be compared to the changes in MeV-GeV particle flux in the troposphere and stratosphere, also showing tens of percent change from solar maximum to solar minimum. The bottom panel contains mean January-February surface temperatures for three eastern U.S. stations, for QBO west phase winters [*van Loon and Labitzke*, 1988]. The excursions by about 6°C are correlated with cosmic ray flux and anticorrelated with the sunspot cycle.

It is of interest that these regional temperature changes, associated with changes in circulation, have agricultural and economic consequences far larger than the changes of a few tenths of one degree Celsius of mean global temperature since the beginning of this century that is considered an apparent response to the increase in greenhouse gases. If for no other reason than to reduce the uncertainty in determining global warming trends, it should be considered important to understand the causes of these apparent responses to solar variability.

In this paper we will present new results on the day-to-day time scale of the apparent tropospheric response to the atmospheric flux of MeV-GeV particles. This suggests the need for further consideration of meteorological processes affected by atmospheric ionization. We will discuss in some detail the new hypothesis linking atmospheric ionization and ice nucleation in high-level clouds, that was outlined by *Tinsley* [1990*b*, 1991]. A mechanism for day-to-day responses to MeV-GeV particle flux may or may not be a mechanism for responses on the decadal time scale. But if a mechanism for day-to-day responses can be identified, any consequences for the decadal time scale could be determined by a theoretical study.

CORRELATIONS ON THE DAY-TO-DAY TIME SCALE

The sudden reduction of MeV-GeV fluxes at the onset of Forbush decreases provides well defined time references (a set of key days) with which to perform superposed epoch analysis of meteorological data in a search for an apparent response. Since the amplitude of the Forbush decrease is only a few percent, only a small meteorological response is to be expected, requiring the superposition of many epochs to allow any such response to be seen against the background of intrinsic meteorological variability. A list of Forbush decreases of more than 3% amplitude observed with the Mount Washington neutron monitor [*NGDC*, 1985] was used by *Tinsley et al.* [1989] as key days for superposed epoch analysis of the variation of the northern hemisphere vorticity area index, (VAI). An apparent response was found for winter (November through March) months. The VAI is an objective measure of the intensification of cyclonic storms and the deepening of low-pressure troughs. It is a measure of the area (in units of 10^5 km^2) covered by values of absolute vorticity above a threshold of 20×10^{-5} s^{-1} plus the area for vorticity above 24×10^{-5} s^{-1}. This was defined by *Roberts and Olson* [1973] following earlier work on the relationship between magnetic storms and tropospheric storms in the Gulf of Alaska and was used by *Wilcox et al.* [1973, 1974] in superposed epoch analysis of the apparent meteorological response to the passage of solar wind sector boundaries past the Earth.

In the present work we have generated a new list of key days for the onset of Forbush decreases, which extends and corrects the previous list. We computed the time derivative of half day average count rates from both the Mount Washington and Climax neutron monitors [*NGDC*, 1989]. Lists were generated by computer search, of days on which the amplitude of the time derivative was algebraically less than -20 counts/hr/day, after smoothing was performed with a 1:2:1 weighted running mean over 3 half days. Where two events with spacing less than or equal to 4 days were found, then the second was ignored unless it was larger in magnitude by a factor of $(1.25)^n$, where n is the number of half days between them. If so, the second one was used and the first ignored. Comparisons were made between the Mount Washington and Climax lists, and the original list, and lists of the arrival of high-speed plasma streams (HSPS) at the Earth, and lists of magnetic storms, to check the quality of the data sets. It was concluded that the Mount Washington events on the *NGDC* [1985] list before April 1956 were probably not reliable owing to instrumental drifts and that there was a typographical error for one event. Climax data was used alone for events from 1953 to April 1956. The time derivative of the count rate was used to define the key day in the present work rather than the depth of the decrease, and differences of up to several days were found between the several lists. When key days from the Mount Washington and Climax lists were separated by one day, the day for the event with the larger magnitude was used. This master list contains events associated with essentially all of the stronger HSPS and magnetic storm events.

Values of the VAI at the 500-mbar pressure level were calculated from the National Meteorological Center octagonal grid data base, which covers the area from 20°N to 90°N. Events on the master list with derivative amplitude D (counts/hour/day) in the ranges of $D < -90$, $-90 < D < -60$, $-60 < D < -40$, and $-40 < D < -20$ were used to generate superposed epoch VAI plots. All ranges except the last showed apparent response. In Figure 2 are shown superposed epoch plots of several solar variability related parameters, and the northern hemisphere 500-mbar VAI, for all events with $D < -40$, from 20 days before to 40 days after the key day. The list of these 279 events from 1953 through 1985 is given in Table 1. Most events were in solar maximum years, with few in solar minimum years, and none meeting the selection criteria in 1953 and 1954. Data for the events in the months April-October are shown in the left panel of Figure 2 and for the remaining months in the right panel. The upper traces are plots of the Mount Washington and Climax hourly count rates, averaged for half-day intervals and then smoothed over 3 half days as before.

The trace second from the top is the superposed epoch plot of the daily *Ap* values, a measure of terrestrial magnetic storm activity, and the third from top is the daily *F*10.7-cm index, which covaries approximately with solar UV [*Barth et al.*, 1990]. The *Ap* and *F*10.7-cm values are from *NGDC01* [1987]. The lowest trace is the northern hemispheric VAI, with a.m. and p.m. values smoothed with a (1:2:1)/4 weighted running mean. The number of events averaged in each trace is generally less than the number of key days which meet the selection criteria, owing to data gaps. All 1-day data gaps are interpolated separately for a.m. and p.m. time series. Two-day gaps are interpolated only if they do not occur within the interval from 2 days prior to the key day to 4 days after the key day, inclusive. Larger gaps are not interpolated, and epochs with gaps remaining that are not filled are dropped from the superposition.

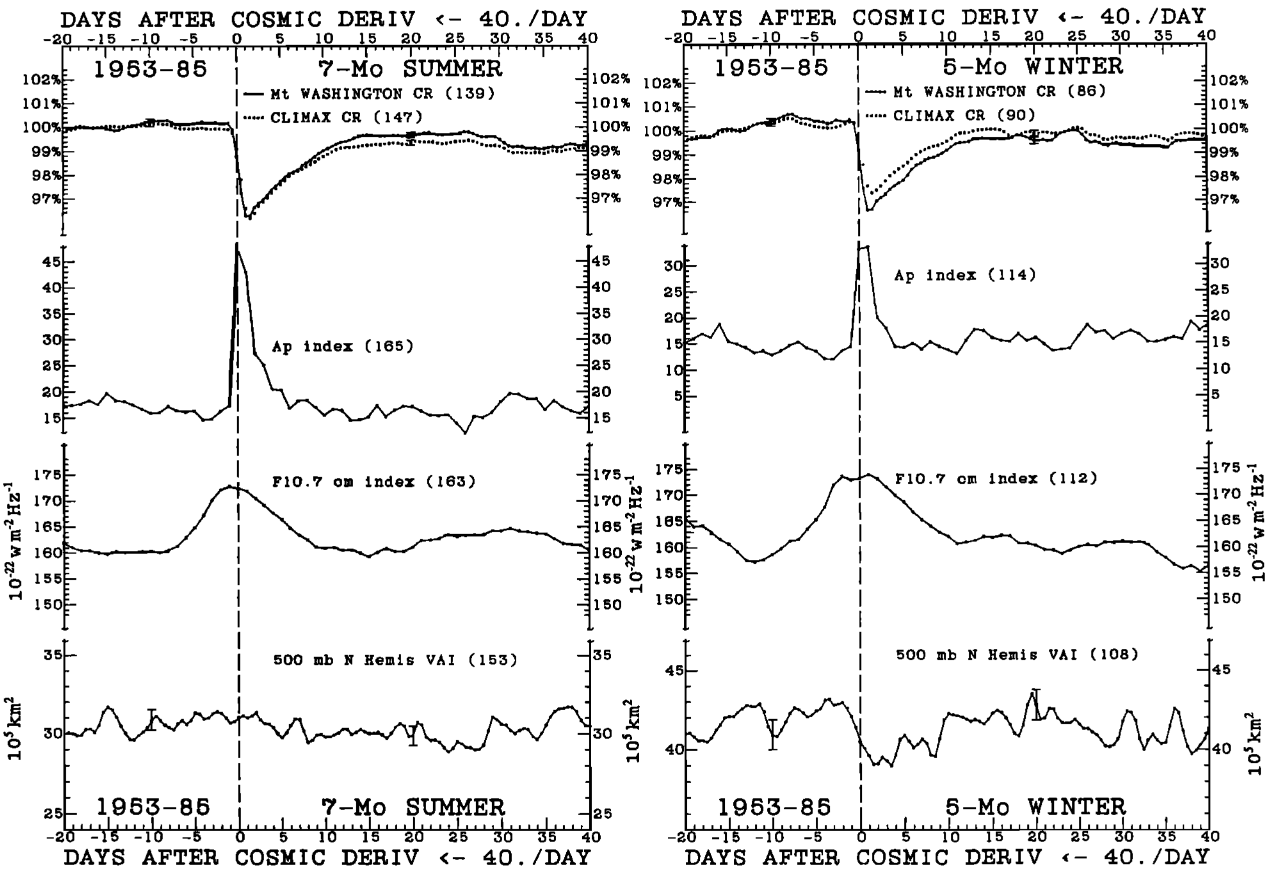

Fig. 2. Superposed epoch plots for nonwinter months (April through October) in the left panel compared to winter months (November through March) in the right panel. The key days (day 0) are the days of onset of Forbush decreases at Mount Washington and Climax as listed in Table 1. The MeV-GeV fluxes at these stations are represented in the top traces as percentage changes from the average of the first 10 days. The *Ap* and *F*10.7-cm indices in the second and third traces down represent the variations of geomagnetic activity and solar ultraviolet flux, respectively. The tropospheric variations in the lowest trace are the average over the northern hemisphere of the 500- mbar vorticity area index (VAI). The numbers in parenthesis are the numbers of events, which are different for different parameters on account of missing data. The lengths of the error bars are two standard deviations of the mean.

All traces show an apparent response on and near the key day, except for the VAI in nonwinter months. The particle flux and *Ap* variations are attributed to the arrival of the disturbed solar wind plasma of the high-speed plasma stream at the Earth. The responsible coronal mass ejections generally occur when a solar active region with enhanced UV emission is facing the Earth; hence the peak in the *F*10.7 cm index which has a width of about half of the 27-day solar rotation period. For the winter VAI trace the average level of hemispheric vorticity is higher than in nonwinter, and the reduction of VAI for 5—10 days starting with the key day (day 0) can be seen to have a similar shape to the reduction in MeV-GeV flux. This is allowing for the internal atmospheric variability, reflected in the VAI variability, which is greater in winter than in summer. The length of the error bars is twice the standard deviation of the mean, which is calculated for the given day (relative to the key day) from the variances from each epoch average.

In Figure 3 the winter events have been subdivided into those with $D < -60$, and those with $-60 < D < -40$; corresponding to events for stronger and weaker Forbush decreases respectively. This division is reflected in the excursions in the traces for the neutron monitor counts, and as might be expected, in the *Ap* and *F*10.7 cm parameters also. The VAI reductions starting on the key day (allowing for internal VAI variability) can be seen to be greater for the stronger Forbush decreases, consistent with the concept of an apparent VAI response to MeV-GeV particle flux changes.

In Figure 4 the winter events for $D < -40$ have been divided into those prior to 1970 and those in 1970 and later. The apparent VAI response starting on the key day can be seen to be present in both halves of the data. Similarly, the results for a subdivision of events into those for November-December and those for January-March (not shown) again resulted in about equal VAI apparent responses in both sets of data.

In Figure 5 the same events have been separated into those for which the equatorial stratospheric winds were from the west (west phase of quasi-biennial oscillation, or QBO) and those for winds from the east (east phase QBO). An apparent response to the MeV-GeV particle flux can be seen in both phases, and it is apparently stronger in the east phase.

In Figure 6 results are shown for $D < -40$ based on separate VAI calculations for three latitude zones and eight longitude sectors. The MeV-GeV particle flux and *Ap* and *F*10.7 cm indices are plotted in the top three traces as before. The lowest trace is the VAI for the low-latitude zone, 20°—40°N, and although this represents about the same surface area as for the 40°—65°N zone in the trace above it, the VAI values are

TABLE 1. List of 279 Key Days Defining Cosmic Ray Forbush decreases for which the time derivative D was More Negative than -40 counts/hr/d, From the Climax and Mount Washington Neutron Monitors

Date	D	Date	D	Date	D	Date	D	Date	D
Nov. 19, 1955	-49	Jan. 27, 1959	-45	Sep. 3, 1966	-68	Mar. 27, 1972	-44	Jun. 8, 1980	-48
Dec. 6, 1955	-52	Feb. 11, 1959	-78	Sep. 14, 1966	-56	May 15, 1972	-64	Jun. 23, 1980	-60
Feb. 12, 1956	-49	Mar. 13, 1959	-42	Sep. 24, 1966	-60	May 30, 1972	-68	Jul. 25, 1980	-65
Feb. 17, 1956	-49	Mar. 26, 1959	-60	Oct. 25, 1966	-44	Jun. 17, 1972	-93	Sep. 2, 1980	-57
Mar. 3, 1956	-45	Apr. 9, 1959	-56	Nov. 17, 1966	-53	Aug. 4, 1972	-245	Sep. 5, 1980	-45
Mar. 12, 1956	-85	Apr. 23, 1959	-48	Dec. 13, 1966	-69	Oct. 18, 1972	-61	Oct. 25, 1980	-52
Apr. 15, 1956	-41	May 11, 1959	-215	Jan. 13, 1967	-56	Oct. 31, 1972	-118	Nov. 10, 1980	-52
Apr. 27, 1956	-88	Jun. 11, 1959	-43	Feb. 15, 1967	-44	Dec. 13, 1972	-45	Nov. 25, 1980	-50
May 12, 1956	-68	Jun. 15, 1959	-42	Apr. 1, 1967	-46	Jan. 19, 1973	-44	Nov. 29, 1980	-52
May 16, 1956	-52	Jul. 11, 1959	-151	May 1, 1967	-57	Apr. 13, 1973	-59	Dec. 19, 1980	-68
Aug. 21, 1956	-47	Jul. 15, 1959	-157	May 8, 1967	-45	May 7, 1973	-40	Feb. 24, 1981	-58
Sep. 1, 1956	-85	Jul. 17, 1959	-150	May 25, 1967	-122	May 13, 1973	-54	Mar. 1, 1981	-47
Sep. 8, 1956	-58	Aug. 19, 1959	-68	Oct. 29, 1967	-43	Jul. 13, 1973	-49	Mar. 26, 1981	-50
Sep. 20, 1956	-53	Sep. 3, 1959	-66	Nov. 22, 1967	-54	Mar. 22, 1974	-44	Mar. 31, 1981	-46
Nov. 9, 1956	-120	Sep. 19, 1959	-73	Jan. 26, 1968	-46	May 14, 1974	-41	Apr. 2, 1981	-58
Nov. 15, 1956	-62	Dec. 3, 1959	-95	Jun. 8, 1968	-43	May 31, 1974	-47	May 11, 1981	-50
Dec. 21, 1956	-44	Jan. 14, 1960	-72	Jun. 11, 1968	-69	Jul. 6, 1974	-60	May 15, 1981	-52
Dec. 25, 1956	-43	Mar. 31, 1960	-152	Jul. 11, 1968	-73	Sep. 13, 1974	-70	May 18, 1981	-95
Dec. 27, 1956	-55	Apr. 27, 1960	-53	Aug. 17, 1968	-52	Oct. 23, 1974	-47	May 31, 1981	-56
Dec. 31, 1956	-70	Apr. 30, 1960	-80	Sep. 3, 1968	-41	Mar. 26, 1975	-48	Jul. 23, 1981	-44
Jan. 21, 1957	-257	May 8, 1960	-108	Oct. 29, 1968	-164	Nov. 28, 1975	-44	Aug. 10, 1981	-64
Jan. 29, 1957	-50	May 22, 1960	-52	Nov. 16, 1968	-59	Feb. 17, 1976	-49	Oct. 3, 1981	-58
Mar. 1, 1957	-48	May 28, 1960	-58	Nov. 24, 1968	-44	Mar. 26, 1976	-42	Oct. 11, 1981	-45
Mar. 10, 1957	-120	Jun. 5, 1960	-52	Dec. 5, 1968	-67	May 21, 1976	-40	Oct. 13, 1981	-97
Apr. 5, 1957	-42	Jun. 27, 1960	-94	Feb. 27, 1969	-50	Sep. 22, 1977	-85	Oct. 20, 1981	-62
Apr. 15, 1957	-46	Jul. 14, 1960	-63	Mar. 16, 1969	-57	Jan. 3, 1978	-90	Nov. 11, 1981	-51
Apr. 17, 1957	-73	Aug. 14, 1960	-42	Mar. 24, 1969	-106	Jan. 11, 1978	-42	Nov. 25, 1981	-40
May 26, 1957	-46	Aug. 28, 1960	-58	Mar. 31, 1969	-76	Jan. 29, 1978	-61	Dec. 29, 1981	-53
Jun. 22, 1957	-45	Sep. 3, 1960	-55	Apr. 12, 1969	-94	Feb. 15, 1978	-221	Jan. 17, 1982	-46
Jun. 30, 1957	-42	Oct. 6, 1960	-110	Apr. 27, 1969	-64	Mar. 8, 1978	-125	Jan. 31, 1982	-89
Aug. 4, 1957	-83	Nov. 13, 1960	-505	May 14, 1969	-106	Apr. 3, 1978	-70	Feb. 11, 1982	-65
Aug. 29, 1957	-173	Nov. 15, 1960	-256	Jun. 8, 1969	-43	Apr. 10, 1978	-60	Mar. 1, 1982	-85
Sep. 2, 1957	-47	Dec. 26, 1960	-52	Sep. 27, 1969	-48	Apr. 18, 1978	-44	Apr. 13, 1982	-41
Sep. 13, 1957	-41	Feb. 16, 1961	-40	Oct. 24, 1969	-46	May 1, 1978	-155	Apr. 25, 1982	-55
Sep. 22, 1957	-57	Apr. 14, 1961	-75	Nov. 9, 1969	-53	Jun. 2, 1978	-69	Jun. 9, 1982	-64
Sep. 29, 1957	-78	May 22, 1961	-47	Nov. 22, 1969	-45	Jun. 26, 1978	-83	Jul. 13, 1982	-236
Oct. 22, 1957	-130	Jul. 13, 1961	-180	Jan. 29, 1970	-60	Jul. 13, 1978	-74	Aug. 6, 1982	-60
Nov. 24, 1957	-50	Jul. 18, 1961	-103	Mar. 31, 1970	-52	Sep. 24, 1978	-95	Sep. 6, 1982	-101
Dec. 17, 1957	-46	Jul. 26, 1961	-74	Jun. 18, 1970	-47	Sep. 29, 1978	-68	Sep. 21, 1982	-82
Dec. 19, 1957	-56	Sep. 30, 1961	-102	Jul. 24, 1970	-85	Nov. 12, 1978	-76	Nov. 24, 1982	-70
Jan. 17, 1958	-49	Oct. 28, 1961	-48	Aug. 16, 1970	-81	Jan. 3, 1979	-43	Nov. 30, 1982	-44
Feb. 10, 1958	-80	Dec. 1, 1961	-73	Sep. 7, 1970	-91	Feb. 18, 1979	-52	Dec. 10, 1982	-46
Mar. 25, 1958	-119	Feb. 5, 1962	-56	Oct. 16, 1970	-43	Mar. 28, 1979	-67	Dec. 27, 1982	-50
Apr. 29, 1958	-41	Apr. 20, 1962	-53	Nov. 7, 1970	-101	Apr. 5, 1979	-58	Jan. 9, 1983	-87
May 8, 1958	-47	May 2, 1963	-69	Nov. 18, 1970	-47	Apr. 25, 1979	-49	Feb. 4, 1983	-134
May 29, 1958	-69	Sep. 17, 1963	-55	Nov. 21, 1970	-54	Jun. 6, 1979	-92	Feb. 27, 1983	-40
Jul. 8, 1958	-94	Sep. 22, 1963	-145	Dec. 14, 1970	-70	Jul. 6, 1979	-117	Mar. 10, 1983	-42
Jul. 21, 1958	-53	Oct. 29, 1963	-73	Jan. 19, 1971	-42	Aug. 1, 1979	-48	Feb. 26, 1984	-42
Aug. 17, 1958	-59	Feb. 8, 1965	-41	Jan. 27, 1971	-61	Aug. 20, 1979	-105	Apr. 26, 1984	-89
Aug. 23, 1958	-74	Apr. 17, 1965	-40	Feb. 12, 1971	-41	Aug. 29, 1979	-41	Sep. 4, 1984	-48
Sep. 3, 1958	-41	Oct. 7, 1965	-50	Mar. 14, 1971	-41	Sep. 17, 1979	-47	Nov. 29, 1984	-40
Sep. 15, 1958	-73	Jan. 20, 1966	-47	Sep. 13, 1971	-48	Oct. 6, 1979	-61	Jan. 25, 1985	-45
Sep. 30, 1958	-58	Mar. 23, 1966	-80	Oct. 6, 1971	-58	Nov. 8, 1979	-44	Apr. 26, 1985	-93
Oct. 22, 1958	-76	May 31, 1966	-51	Oct. 28, 1971	-58	Feb. 6, 1980	-99	Jul. 12, 1985	-43
Nov. 11, 1958	-52	Jul. 8, 1966	-50	Dec. 17, 1971	-74	Mar. 5, 1980	-46	Dec. 18, 1985	-45
Jan. 9, 1959	-49	Aug. 30, 1966	-120	Mar. 6, 1972	-67	Apr. 3, 1980	-55		

much lower, owing to the less dynamic nature of the atmosphere in this zone. While the VAI response to the MeV-GeV flux is apparent for the 40°—65°N zone, it is weak or absent in the low-latitude zone. The fifth trace up is the VAI for the 65°—85°N latitude zone, which represents a small but quite dynamic region of the globe; it too has a weak or absent apparent response to the MeV-GeV flux. The VAI was calculated for eight equal longitude sectors in the mid-latitude 40°—65°N latitude zone; these being 30°W—75°W, 75°W—120°W, etc. Results for the four predominantly ocean sectors 15°E—30°W, 30°W—75°W, 120°W—165°W, and 165°W—150°E were co-added, as were the remaining four predominantly continental areas. The results are shown in the third and fourth traces up from the bottom. The apparent response of the VAI to the MeV-GeV particle flux can be seen in the ocean sectors, but it is weaker in the continental sectors.

As a final piece of data analysis a test was made to see if the large excursions in solar UV, as represented by the *F*10.7 variations in Figures 2—6 beginning about a week before the Forbush decrease key days, might be a better candidate for a

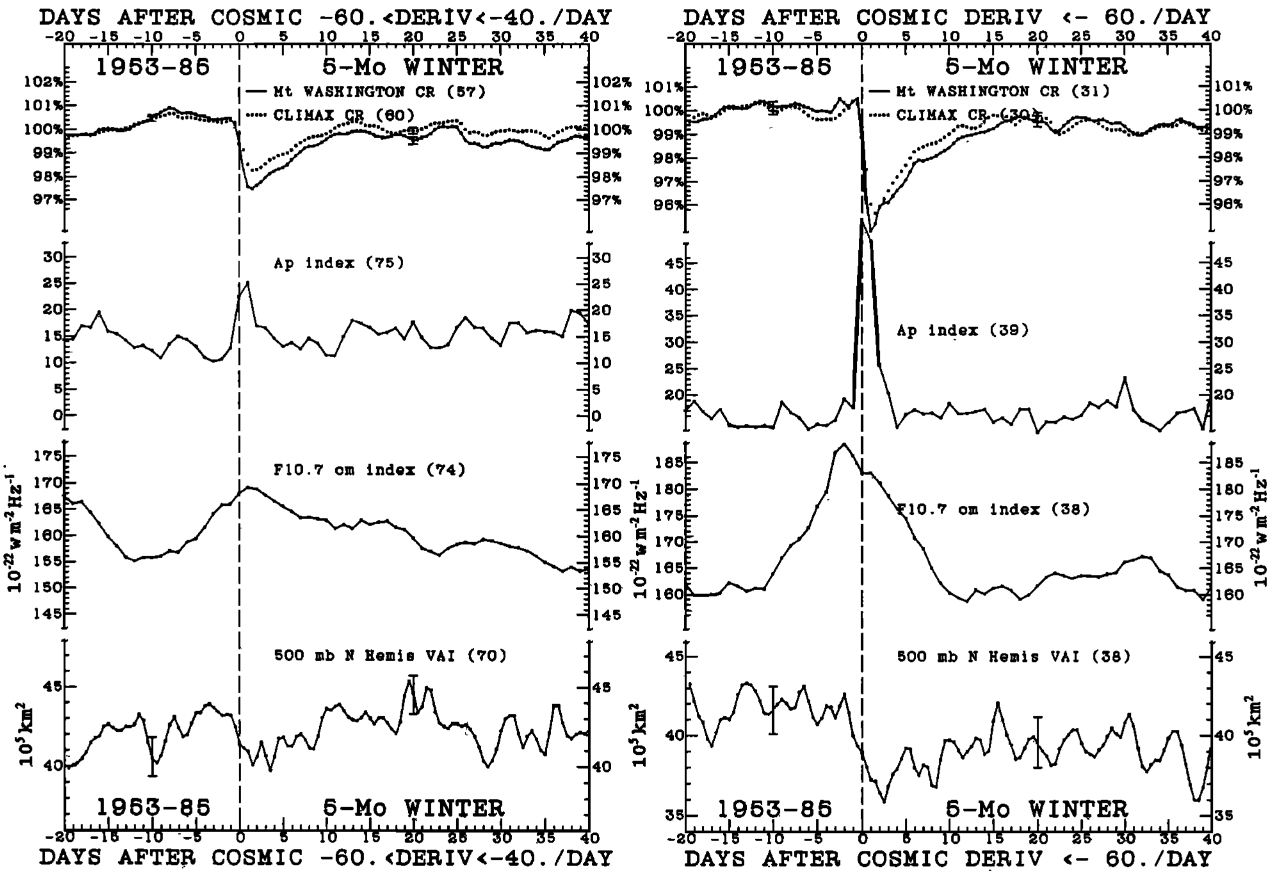

Fig. 3. Superposed epoch plots for (left panel) smaller Forbush decreases compared to (right panel) larger Forbush decreases, for winter months, with format as in Figure 2.

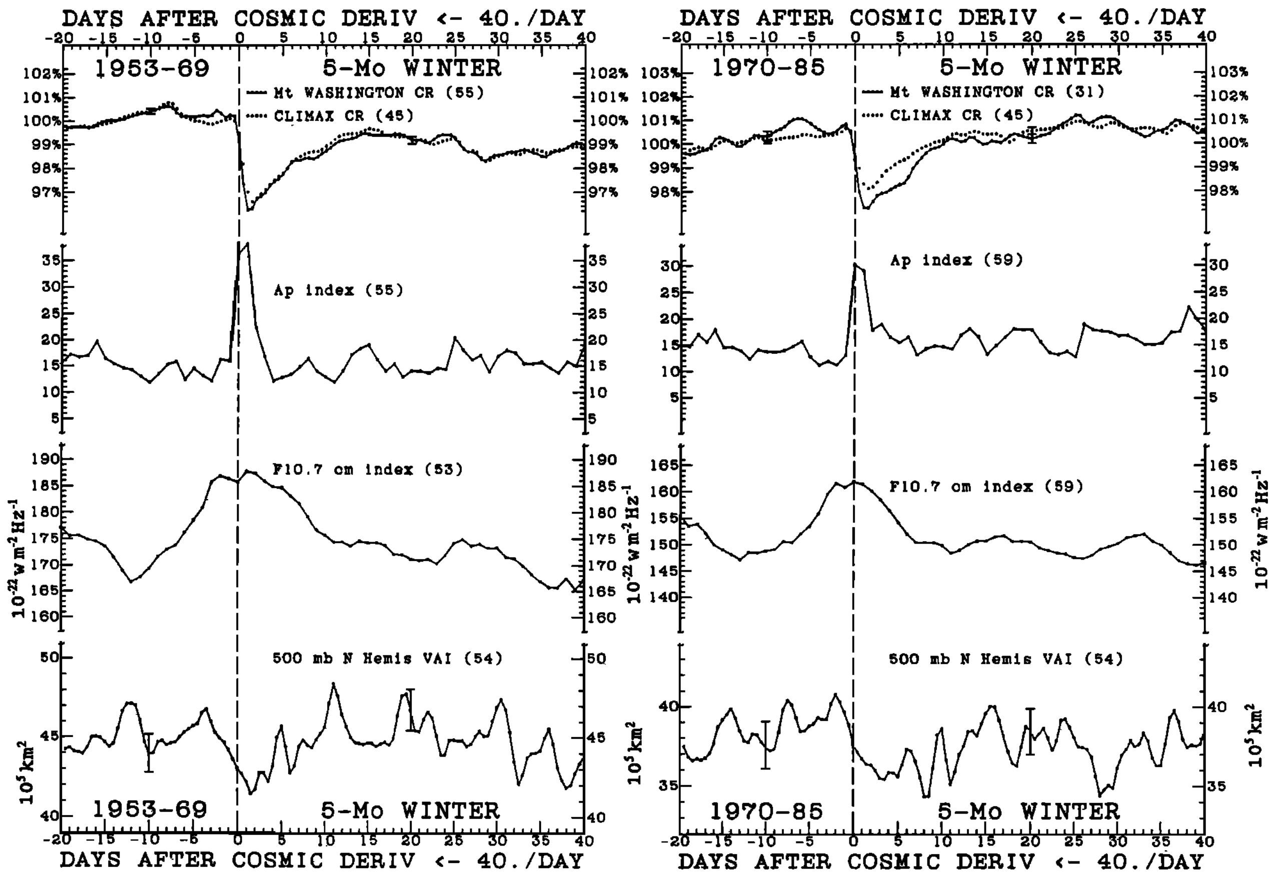

Fig. 4. Superposed epoch plots for winters (left panel) prior to 1970 compared to those for winters in (right panel) 1970 and later, with format as for Figure 2.

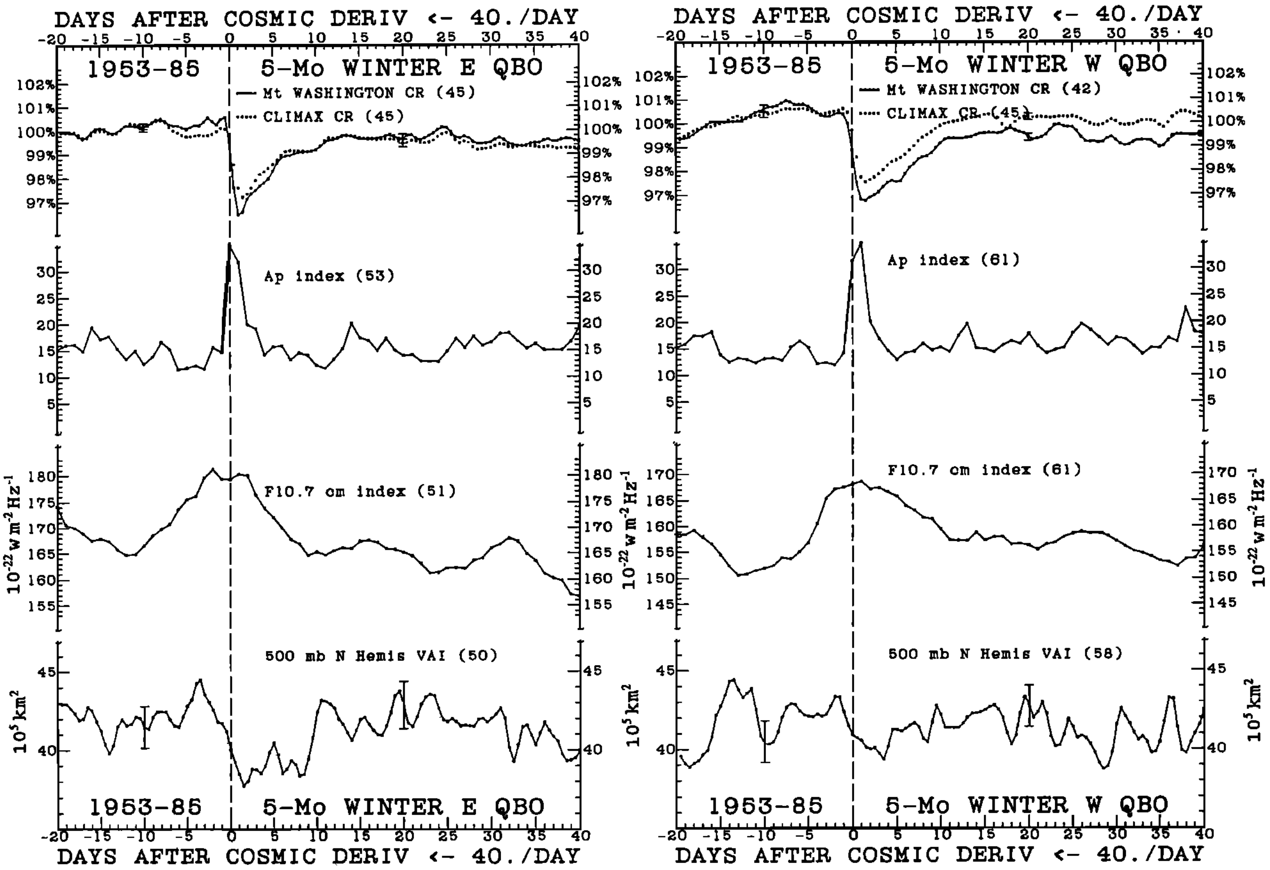

Fig. 5. Superposed epoch plots for winters with (left panel) east phase QBO compared to winters with (right panel) west phase QBO, with format as for Figure 2.

VAI forcing agent than the MeV-GeV flux. In constructing Figure 7, two sets of key days were obtained from a computer search for days in which negative or positive derivatives of the daily *F*10.7 values maximized, over an eleven day interval of the time series smoothed with a triangular weighting function. About 130 winter key days with the largest *F*10.7 derivatives in each list were used to construct the two superposed epoch plots in Figure 7, in the same manner as for the Forbush decrease key day list, with negative derivatives in the left panel and positive derivatives in the right panel. Note that the peak to trough amplitudes are about 45 *F*10.7 units, compared to about half that amount for Figures 2—6, and yet in Figure 7 there are no apparent VAI responses near the times of peak *F*10.7. This is consistent with the discussion in the introduction suggesting that short-term UV forcing of the VAI would be unlikely.

For completeness we note that a test to see if *Ap* variations might be a better candidate for VAI forcing than the MeV-GeV flux changes was discussed by *Tinsley* [1990*a*]. When an analysis having key days selected for larger average *Ap* and smaller average MeV-GeV flux changes was compared with a parallel analysis having key days selected for smaller average *Ap* and larger average MeV-GeV flux changes, the latter analysis showed a significantly larger VAI apparent response. Thus the conclusion was that MeV-GeV flux was to be preferred as a candidate for a short-term forcing agent over magnetic field variations.

DISCUSSION OF CORRELATIONS

The apparent response of the vorticity area index, which is a measure of the intensity of cyclonic storms, to the MeV-GeV flux, representing atmospheric ionization, is greatest in winter, which is the time of maximum cyclogenesis; and greatest in the mid-latitude ocean sectors, which are the regions of maximum cyclogenesis. These results are consistent with those of *Stolov and Shapiro* [1974], who examined the variations of the 700-mbar geopotential height correlated with the onset of magnetic storms, and found maximum response in winters in the north Atlantic and north Pacific oceans. The results are also consistent with those of *McDonald and Roberts* [1960] and *Roberts and Olsen* [1973] for wintertime 300-mbar trough development in the north Pacific.

The results of Figure 7 and the discussion in the introduction suggest that UV variations are unlikely to be the forcing agent for the VAI variations shown in Figures 2 through 6. Also, the shape of the apparent VAI responses is a better fit to the MeV-GeV flux variations than to the *F*10.7-cm variations. The same could be said about the fit to the *Ap* variations, since although the latter have the same sharp onset as the Forbush decreases, they have a much faster decay. While short-term forcing of tropospheric dynamics by UV variations or magnetic field variations seems unlikely, this does not rule out the possibility of forcing on the longer time scale of the 11-year sunspot cycle, when there would be more time for dynamic or chemical coupling to be effective between the upper stratosphere and the troposphere. Observations of changes in ozone concentration correlated with 27-day and 13-day solar UV variations were found by *Keating et al.* [1987]. However, these were above 30 km and within 20° of the equator. If there is a mechanism in which a terrestrial input related to solar variability is forcing changes in tropospheric dynamics on the day-to-day time scale, a connection via

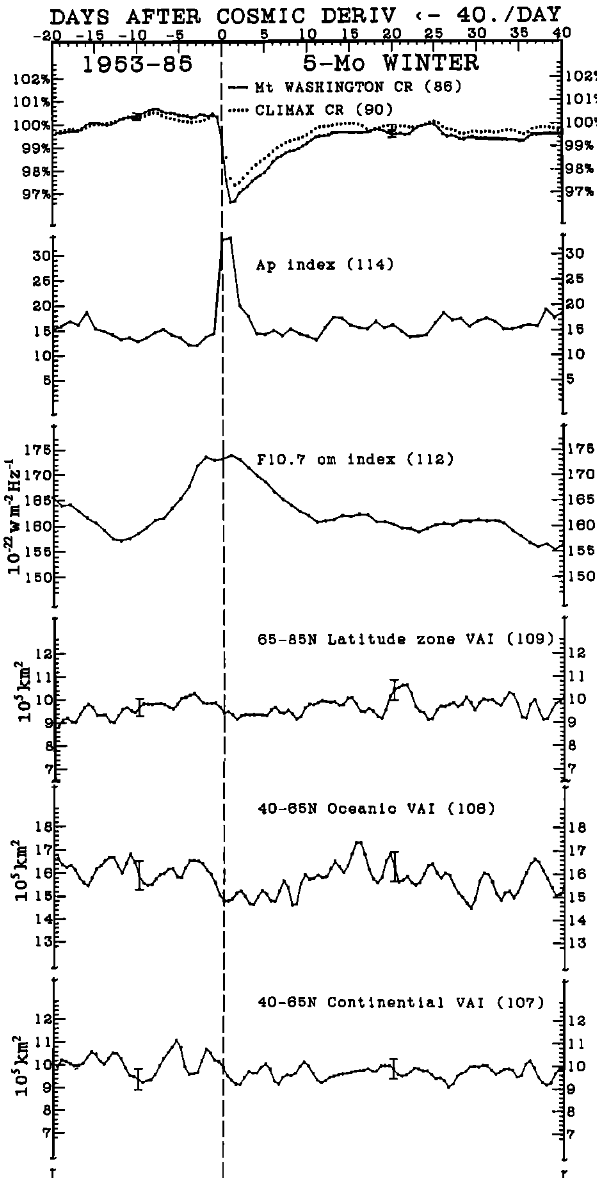

Fig. 6. Superposed epoch plots with the northern hemisphere divided into regions. The events are for winter, with the upper three traces as for Figure 2 (winter). The lowest trace is the VAI for the low-latitude zone. The next trace up is the VAI for the mid-latitude zone. The fifth trace up is the VAI for the high-latitude zone. The third trace up is for continental sectors in the mid-latitude zone, and the fourth trace up is for oceanic sectors in the mid-latitude zone, with boundaries as described in the text.

MeV-GeV particle fluxes would seem to be the most promising for further research.

There is a tendency in Figures 2—6 for the drop in the VAI at about the time of the key day to start before the cosmic ray flux begins its decrease, suggesting that something other than the cosmic ray flux is causing the drop. There are two aspects to this. The early start of the VAI decrease represents a second-order effect, with integrated effect much more comparable to the noise than the first-order effect of the VAI decrease which lasts about a week, and is correlated in amplitude with the changes in cosmic ray flux. Secondly, it was shown by *Wilcox et al.* [1973, 1974] and confirmed by *Tinsley et al.* [1989] that a dip in VAI lasting only 2 or 3 days is associated with solar wind sector boundary crossings. While most of these are unrelated to magnetic storms, there is a tendency for those during active conditions to occur two or three days before Forbush decreases. If the VAI drop before Forbush decreases is real (which is highly uncertain), it is consistent with a sector boundary effect.

The correlations on the day-to-day time scale found for the season and locations for cyclogenesis suggest the capability for changes in the MeV-GeV particle flux to alter the processes of cyclone development. The energy flux for the MeV-GeV particles, of about 10^{-3} ergs cm^{-2} s^{-1}, is about a factor of 10^7 less than the energy involved in the apparent tropospheric response, of roughly 10^{-3} watts cm^{-2}. Effects of atmospheric ionization on nucleation processes in thermodynamically unstable cloud environments have been suggested previously [*Ney*, 1959; *Dickinson*, 1975], and conceivably could provide the initial and perhaps the major part of the needed amplification by a factor of 10^7, in a time scale of less than a day. Winter cyclones over oceans provide suitable cloud environments, with opportunities for further amplification through the unstable convective processes resulting from the relatively large ocean-atmosphere temperature difference. This is especially so for the location where the decadal variation in cyclone frequency of Figure 1 was found, which is the longitude region of highest magnetic latitude, and of largest changes in atmospheric ionization. Figure 1 shows that tens of percent change in MeV-GeV particle flux correlate with tens of percent change in cyclone frequency on the decadal time scale, and Figures 2 through 6 show that a few percent change in MeV-GeV particle flux correlate with a few percent change in cyclone intensity (measured above a threshold by the VAI) on the day-to-day time scale.

Dickinson [1975] considered that ions might induce nucleation of gaseous H_2SO_4 to form cloud condensation nuclei, with changes in drop size distribution affecting cloud radiative forcing of atmospheric dynamics. Changes in atmospheric ionization also produce changes in the atmospheric electric field, through changes in conductivity in the global electric circuit. *Roble and Hays* [1982] suggested that changes in the electric field might affect cloud processes and atmospheric dynamics. The collision of MeV-GeV particles with N_2 and O_2 molecules in the atmosphere is a source of a number of reactive minor chemical species, including the oxides of nitrogen [*Nicolet*, 1975]. While the lifetimes against destruction for HNO_3 and related species are too long for production rate changes to affect short-term processes in the lower stratosphere, this may not be true near the tropopause, where ice processes may rapidly remove NO_x from the region [*Murphy et al.*, 1990]. Thus processes involving chemical and electric field changes should be considered as having possible effects on cloud nucleation processes, in addition to any effects due to changes in ion concentration. *Tinsley* [1990*b*, 1991] suggested that the rate of freezing of supercooled water

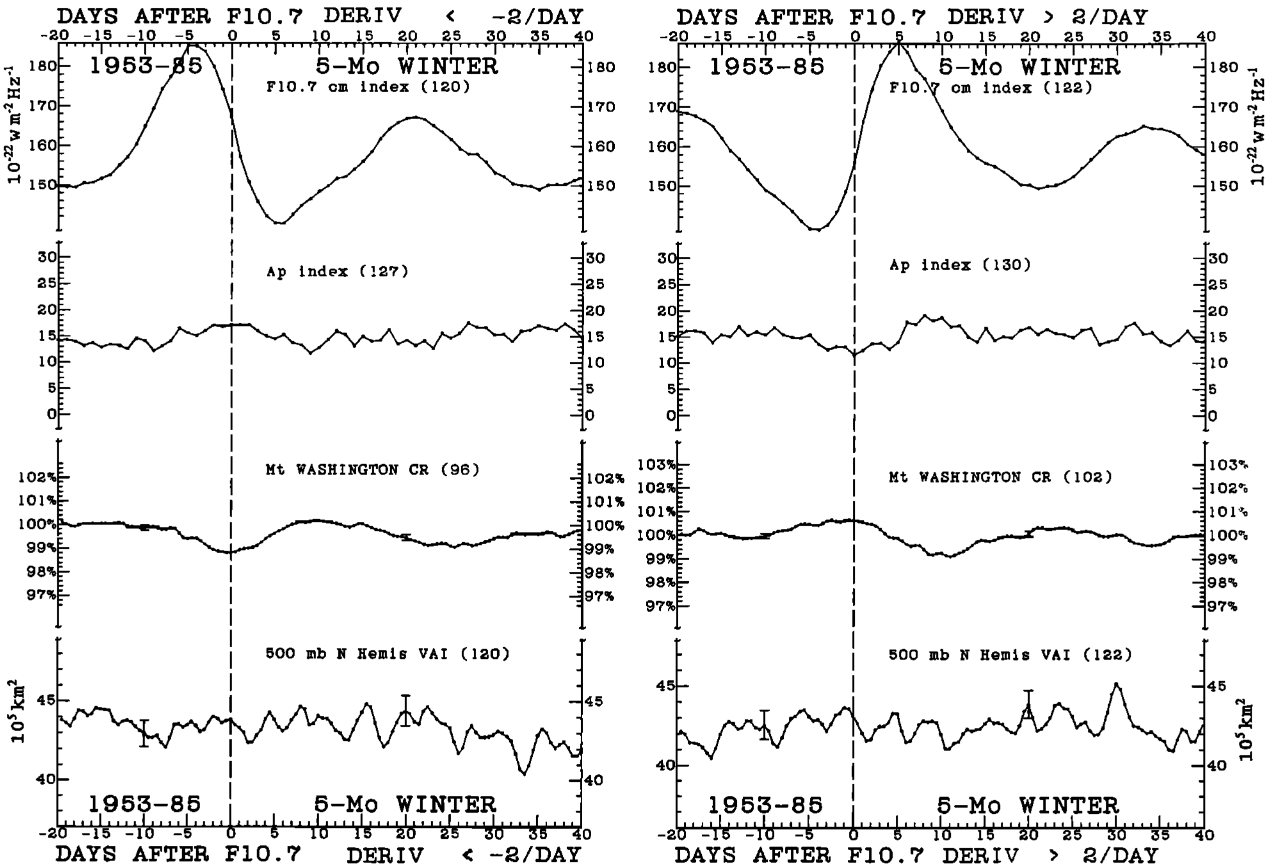

Fig. 7. Superposed epoch plots for winter months 1953-1985, with key days those for which the derivative of the time series of the daily *F*10.7 index had a (left panel) maximum negative value, and those for which the derivative had a (right panel) maximum positive value. For each panel the superposed *F*10.7 variation is plotted in the top trace; the *Ap* variation in the second trace; the MeV-GeV flux variation in the third trace, and the VAI variations in the lowest trace.

droplets in high-level clouds might depend on atmospheric ionization. For high clouds in winter cyclones the moist, unstable environment is such as to further amplify the effect, giving a promising fit to the time scale, location and cyclogenesis context of the correlations discussed above. Figure 8 is a cartoon showing a chain of probable consequences, for cyclone intensities and the general circulation, resulting from effects of MeV-GeV particles on the nucleation and/or initial growth rates of ice crystals in the high-level clouds of cyclones. We refer to such hypothetical effects of MeV-GeV particles generally as "electrofreezing." The key result of any such process is an increase in the rate of formation of the larger ice crystals in the size distribution. These are then capable of sedimenting to lower altitudes. A number of alternatives exist for specific physical mechanisms to achieve this, although the current uncertainties regarding initial ice nucleation processes and ice crystal growth and multiplication processes in clouds allow little more than speculation at this time. To stimulate research, we note that possible processes include but are not limited to: (1) an increase in the "sticking coefficient" and effective collision rates of the larger charged droplets with uncharged and oppositely charged aerosols acting as contact ice nuclei, producing an increase in the contact ice nucleation rate; (2) an increase in the nucleating ability of contact ice nuclei in the presence of the microscopic but large electric fields due to particle charging, as compared to the nucleating ability of uncharged ice nuclei; and (3) changes in atmospheric electric fields affecting the transport of light atmospheric ions into regions depleted of ionization by higher water vapor or liquid water content. The general fair weather field may be amplified by small-scale induction processes near cloud tops. An increase in transport of ions would enhance processes (1) and (2) if they are effective.

The steps following the initial nucleation and growth of ice crystals are standard meteorology and fairly straightforward, and we will now review them, before returning to discuss aspects of those possible first steps. The growth of micron sized ice crystals to millimeter size at the expense of supercooled water droplets (the Wegener-Bergeron instability) is reviewed by *Fleagle and Businger* [1980, p. 120]. This instability is due to the saturated vapor pressure over ice being less than that over liquid water. The resulting millimeter-size ice crystals sediment (in clear air as fallstreaks) [see *Wallace and Hobbs*, 1977, p. 244] and in the context of winter cyclones can act through the "seeder feeder" process to induce glaciation in midlevel clouds. *Rutledge and Hobbs* [1983] modeled the process for warm frontal rainbands, with a reasonable agreement with observations, and an effective doubling of the rate of precipitation. The glaciation process releases latent heat of fusion in midlevel clouds. An interesting example of the consequences for altocumulus clouds, when the air is clear below them, is apparent in the phenomenon of "holes in clouds" [*Hobbs*, 1985]. Recent photographs are given by *Phillips* [1990] and *Holman* [1990]. The holes are considered to be produced when the clouds begin to glaciate in a localized region, and the latent heat release sets up a convection cell, with upwelling in the center

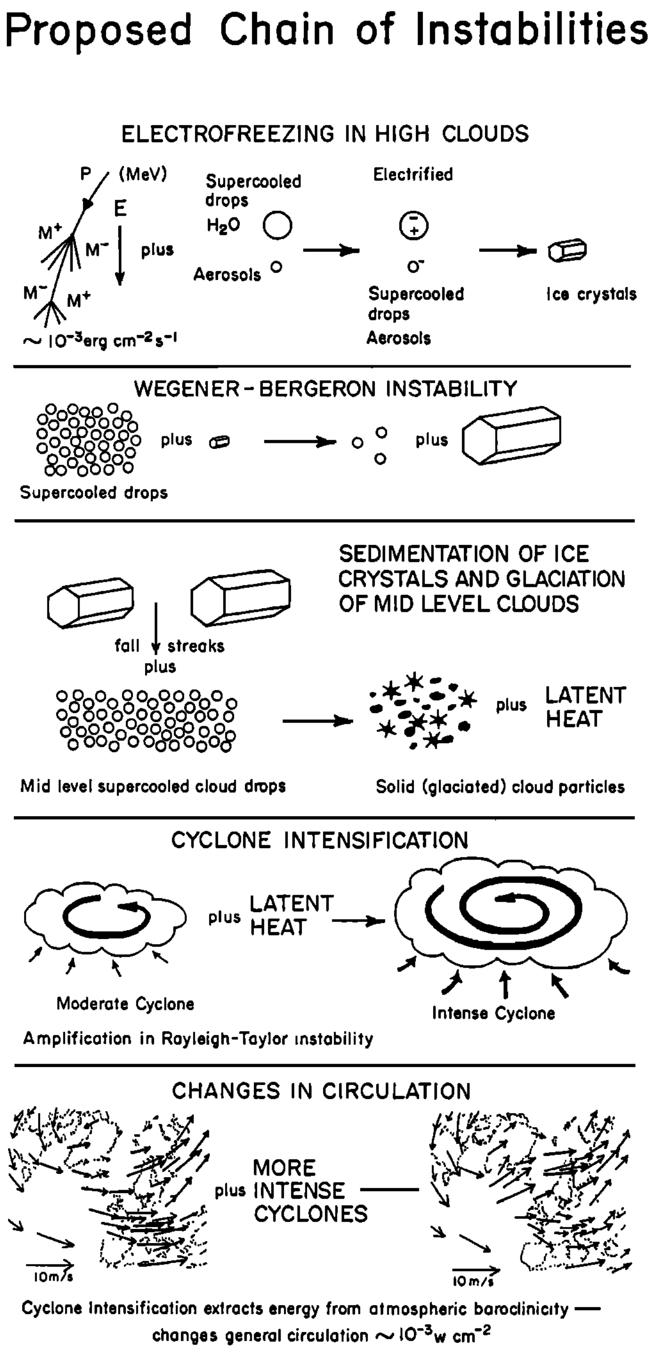

Fig. 8. Schematic of the series of instabilities proposed to explain the apparent relationship between changes in MeV-GeV flux and changes in the general circulation in the troposphere. For explanation and literature references, see text.

and downwelling at the edges, producing a hole in the cloud with sharply defined edges. Similar, but more intense and chaotic events are likely to occur in winter cyclones, further amplified by increasing the upward transport of latent and sensible heat from the relatively warm ocean surface.

The growth of balanced cyclones by this sort of diabatic heating has been treated theoretically by *van Delden* [1989*a*, *b*]. If the cyclone is already relatively intense and has a warm core, then the release of diabatic heat will further intensify it (i.e., deepen the central low), by converting the kinetic energy of the general circulation into eddy kinetic energy. This will not be the case for a weak or cold core cyclone. The theory has been worked out for balanced (axisymmetric) cyclones; however, it seems likely that similar results will apply to unbalanced warm core cyclones where there is readily available latent and sensible heat. Such is the case for winter cyclones east of the North American and Asian continents, where cold continental air encounters a relatively warm ocean. The deepening of cyclones depends on the degree of baroclinicity, which is strongest in winter. As noted by *Tinsley et al.* [1989], a greater frequency of cyclonic disturbances leads to a greater divergence of momentum flux, by a greater generation of waves, including gravity waves, that propagate out of the region. As discussed for example by *Hoskins* [1983, pp. 190-193] and modeled by *Pauley and Smith* [1988], the effect of storm intensification, due for example to increased latent heat release, is to cause the downwind storm track to shift poleward.

The bottom panel of Figure 8 is actual data from *Venne and Dartt* [1990], which shows changes in the mean February-March 700-mbar wind velocities for QBO west phase winters, with sunspot maximum (minimum cosmic ray flux) on the left, and sunspot minimum on the right. These changes are consistent with the poleward shift of storm tracks for six solar minima shown in Figure 1.

The major questions to be addressed in the chain of instabilities outlined in Figure 8 concern the first steps, that of a possible connection between changes in ice nucleation and initial growth processes on the one hand, and changes in the ambient ionization, or electric fields, or minor chemical species produced by the MeV-GeV particle flux on the other hand. In the following sections we will address aspects of these questions.

CONTEXT OF ICE CRYSTAL NUCLEATION AND GROWTH IN HIGH-LEVEL CLOUDS

The context which appears to be most likely for ice nucleation and growth to millimeter sized crystals, capable of falling out to affect lower level clouds, is the dynamic one of the uplift, cooling, and saturation of moist air. Temperatures would be well below freezing, and condensation of the saturated vapor is initially to the liquid phase, since there is a general dearth of ice nuclei compared to condensation nuclei by a factor of 10^6 or more, leading to most of the vapor forming droplets of supercooled water. Such processes have been reviewed by *Wallace and Hobbs* [1977] and *Fleagle and Businger* [1980] and recently in the context of stratospheric chemistry and solar variability by *Mohnen* [1989].

Growth of water droplets and ice crystals and freezing of droplets takes place in the context of continuing uplift, cooling, and maintenance of water vapor pressure above the saturation value for ice, and perhaps above that for water as well, depending on the dynamics and the competition for vapor between ice and water. Such processes have been modeled by *Sassen and Dodd* [1988] and *Heymsfield and Sabin* [1989] for clouds with temperatures ranging below -40°C, in which case homogeneous ice nucleation is likely to dominate. Models for clouds at temperatures down to -32°C, showing variations in the amount of supercooled water at cloud tops as a function of temperature, updraft speeds and initial ice particle concentrations, have been given by *Rauber and Tokay* [1991]. They did not model the processes of initial ice nucleation, which are not well known. The problem was addressed by *Hobbs and Rangno* [1985] who presented extensive observational data, and concluded that mixing of cloudy and ambient air near cloud tops might be important, since it would facilitate the partial evaporation of drops and the probability of their contact with aerosols from the ambient air. Some of these aerosols might then be effective as contact ice nuclei. The initial ice formation process was correlated with the presence of relatively large ($\sim$20 micron) droplets. For affecting the chain of instabilities of Figure 8 we require that effects of ionization, electric fields, or changes in particle-produced chemical minor constituents affect the initial ice crystal population at cloud tops by changing the size distribution. For example, with early electrofreezing of the larger cloud droplets (with larger charge), the resulting micron-sized ice crystals would rapidly grow, in the context of abundant vapor, to millimeter-sized crystals which would fall and glaciate lower level clouds. On the other hand, with less electrofreezing, large and small drops would freeze later on contact with ice nuclei at a lower temperature, or freeze homogeneously near -40°C. With lower vapor pressure and more competition for vapor, fewer ice crystals would grow to millimeter size to fall and glaciate lower clouds.

DISCUSSION OF LABORATORY EXPERIMENTS

Laboratory experiments relative to the question of an increase in the rate of collection (i.e., of collision and "sticking") of neutral aerosols by charged as compared to neutral raindrops were discussed by *Barlow and Latham* [1983]. For water drops of radii of from 270 to 600 microns, carrying a relatively large number of elementary charges, the collection efficiencies were found to increase by about two orders of magnitude above rates for uncharged drops. The extent to which the process is effective for smaller drops with smaller charges, and the rates for charged aerosols approaching oppositely charged drops, remains to be determined.

Other laboratory data are relevant to the question of whether nucleation of ice is enhanced by the presence of electric charges or electric fields. *Gabarashvili and Gliki* [1967] demonstrated that negatively charged crystals of cholesterol or naphthalene in bulk samples of supercooled water nucleated ice at much higher temperatures than uncharged crystals of these substances. Positive charging inhibited the effect. *Varshneya* [1969] found that ice nucleation occurred along the line of ions produced by irradiation of bulk samples of supercooled water by MeV particles, and he provided a theory for the effect [*Varshneya*, 1971]. *Pruppacher* [1973] found that the freezing temperature of supercooled water droplets, 100 to 350 microns radius, was considerably raised when contacted by predominantly negatively charged amorphous sulphur particles which, when uncharged, are known to be poor ice forming nuclei. Nucleation of ice is discussed by *Hobbs* [1971, chap. 7]. Perfect crystals of substances such as AgI or silica, which have quite good lattice match to ice, are found to be not as efficient nucleators as crystals of the same substances with impurity sites on which ice can form, and on which there is a balance between hydrophilic and hydrophobic sites, and between positive and negative surface charges [*Edwards and Evans*, 1962; *Hamilton et al.*, 1968].

Experiments by *Doolittle and Vali* [1975] in which uniform electric fields of up to 6×10^3 V cm^{-1} were applied across individual drops failed to produce freezing. Similarly, *Pruppacher* [1973] found that uniform fields up to 2.5×10^4 V cm^{-1} would not cause freezing of columns of water encased in a polythene tube. *Dawson and Cardell* [1973] found that the collision of pairs of supercooled drops (-8°C to -15°C) of highly purified water in filtered air in the presence or absence of electric fields up to 4×10^3 V cm^{-1} did not induce freezing. (However, with air from which the aerosols had not been removed the freezing rates were higher, very erratic, and increased with electric field.)

An interpretation of these negative results, taken in conjunction with the positive ones mentioned earlier, would be that much stronger fields, of the order of 10^6 V cm^{-1}, such as are found at microscopic pointed surfaces of charged bodies, may be essential features in orienting water molecules in a microscopic volume, and thus in initiating nucleation. There is an analogy to conditions in Wilson cloud chambers. There the supersauturation ratios are several hundred percent, so that the vapor pressure is close to the value at which homogeneous vapor-liquid nucleation takes place. Then even a single ion can decrease the potential energy of an embryonic cluster of a few dozen molecules, so that it is stabilized against dissipation, and can grow into a macroscopic droplet. (The amplification factor as a ratio of the energy of the latent head converted, to the energy to create the ion, can be more than 10^{14}.) In a supercooled water droplet, at temperatures approaching the homogeneous ice nucleation temperature of -40°C, ions will similarly decrease the potential energy of any group of molecules that forms an incipient ice embryo, stabilizing it so that it has a greater chance to grow. However, other conditions need also to be met. For vapor-liquid nucleation, no particular orientation of the water dipoles is required at the time the ion decreases the potential energy of the embryonic liquid molecular cluster and stabilizes it, but for ice nucleation the dipoles need to be oriented and arranged into the ice configuration. The points on which negative charges reside on the crystals of the complex molecules of cholesterol and naphthalene may provide a suitable complex charge configuration to do so, as would the field structure of impurity sites, crystal dislocations, and regions between hydrophilic and hydrophobic areas on other crystals. Thus if electric charges have significant effects for nucleation with contact or embedded ice nuclei, it may be that not one but several elementary charges are needed, distributing themselves on both the ice nucleus or the water surface, to provide the complex charge distribution. Laminar flow may also be important. *Abbas and Latham* [1969] discuss a number of experiments from which they infer that freezing of a supercooled droplet can be initiated when the surface is drawn into a liquid filament. *Pruppacher* [1963] found that a strong electric field produced a movement of supercooled drops on a solid surface that was simultaneous with them freezing. His experiments were interpreted by *Loeb* [1963] and *Abbas and Latham* [1969] as support for the importance of simultaneous electric fields and laminar flow in orienting ice embryos and adjacent water molecules to initiate freezing. Such processes may be important in high clouds, when charged supercooled droplets approach aerosols or droplets with induced or opposite charges, and the water flows to form a small neck in the high electric field region between them, as they begin to coalesce. The above processes could be regarded as electrical effects increasing the ice nucleating ability of contact ice nuclei.

Our conclusion regarding laboratory experiments generally is that they are suggestive but not definitive concerning possible effects of electric charges attached to supercooled drops and aerosols on the rate of ice nucleation. If electrofreezing of single droplets is indeed caused by some number of ions less than about 100, then the energy to create the ions is still amplified by a factor of the order of 10^{12} by the latent heat released in the subsequent production of millimeter sized ice crystals.

NATURAL CHARGING OF AEROSOLS AND DROPLETS

The molecular ions (air ions) produced by the passage of MeV-GeV particles through the air are likely to attach themselves to an aerosol or water droplet on collision. As a result of collisions by both positive and negative ions, the aerosols and droplets tend towards a distribution of charge which in simple cases approximates a Boltzmann distribution of energies. Theoretical descriptions of this process have been reviewed for example by *Twomey* [1977, chap. 11] and *Hinds* [1982, chap. 15]. In the Boltzmann distribution the average number of elementary charges on a particle is a function of the radius, with most of the particles having zero charge for radii less than 10^{-2} microns, and average numbers of charges (counting positive or negative charges regardless of sign) varying approximately as the square root of the radius. The average number of charges is about 1 for a radius of 10^{-1} microns; about 3 for 1 micron; and about 10 for 10 microns.

Initially, the droplets in a cloud are most likely to have zero charge, with only a small fraction having a single charge, corresponding to the Boltzmann distribution for the condensation nuclei on which they form. As they grow, they will charge toward a Boltzmann distribution with a higher mean charge at a rate proportional to the ambient ion concentration. In the scenario for ice nucleation discussed by *Hobbs and Rangno* [1985] the time scales for droplet growth and mixing with ambient air are likely to be short compared to the time for achieving Boltzmann equilibrium, in which case the average charge on the droplets would be proportional to the ambient ion concentration, and thus to the MeV-GeV particle flux.

QUANTITATIVE CONSIDERATIONS

The MeV-GeV particles have an energy flux of $\sim 10^{-3}$ erg cm^{-2} s^{-1}. An amplification of this energy flux by a factor of $\sim 10^7$ is necessary to account for the 10^{-3} w cm^{-2} of energy flux represented by the change in vorticity area index, or the change in the strength of the general circulation. (These changes consist of a redistribution of energy rather than a change in total atmospheric energy.) As noted, amplification by much more than a factor of 10^7 can occur in nucleation processes. This would compensate for the utilization of only a small fraction of the ionizing flux and would not require further amplification from the Raleigh-Taylor and baroclinic instabilities, although these are likely to contribute. It is not known how many ions would be needed to induce electrofreezing of a micron-sized droplet, but we will show that there are adequate numbers of ions present. *Rutledge and Hobbs* [1983] used a seeder ice concentration of 7 ℓ^{-1} (i.e., 7×10^{-3} cm^{-3}) in their models of the "seeder-feeder" process. These concentrations are consistent with measured values in fall streaks. With an estimated fall speed of about 1 ms^{-1}, [*Wallace and Hobbs*, 1977, pp. 196-197], then the downward flux of ice crystals is 7×10^{-1} cm^{-2} s^{-1}. At tropopause heights the production rate of ions is about 10 cm^{-3} s^{-1} [*Neher*, 1971] and if the electrofreezing process is to occur in a cloud layer 100 m thick, then the column ion production is about 10^5 ions cm^{-2} s^{-1}. Thus we see that there about 10^5 ions that could be available for the production of each sedimenting ice crystal by electrofreezing.

Rutledge and Hobbs [1983] found that the above fluxes of seeder crystals produced roughly a doubling of the precipitation rates in warm frontal rainbands. This would be associated with a doubling of net latent heat release in the rainbands. According to *Mason* [1971], the generation of precipitation by ice processes in clouds (the Wegener-Bergeron-Findeisen process) is probably responsible for 90% of continental air mass precipitation in mid-latitudes. Thus the latent heat release by the seeder-feeder process is a significant fraction of the diabatic heat released in cyclones and would be adequate to induce the intensification as modeled by *van Delden* [1989*a*, *b*].

Of course, during Forbush decreases there is actually a reduction in MeV-GeV flux, with a reduction in all the above processes. A consequence of the electrofreezing hypothesis is that electrofreezing should be a basic element in the production of seeder ice crystals in general, with the variations we have been studying representing a few percent reduction for Forbush decreases and a few tens of percent change for the decadal variations. The role of the QBO remains unclear but may be important in terms of dynamic coupling and chemical transport between the stratosphere and troposphere, since the amplitudes of both short-term and decadal apparent responses are different for the different QBO phases.

The role of cloud radiative forcing remains unclear. Changes in ice nucleation and sedimentation will affect the ice-liquid ratio and particle concentrations and size distributions in high-level clouds. These will have climatological effects via changes in visible albedo and in outgoing longwave radiation. The absorption coefficient in the 11-12 micron wavelength region is several times larger for ice as compared to water. A change in upper level cloud opacity by 20% would produce heating rates in the column below of the order of 0.1°C/day, which as a differential across a zone 15° in latitude would lead to changes in zonal winds at tropopause altitudes of the order of 2 m s^{-1} [*Dickinson*, 1975]. It remains to be evaluated how much of the decadal scale tropospheric variability results from this as compared to the cumulative dynamical consequences of storm intensification. Also, the relative roles of forcing on the decadal time scale by MeV-GeV particles as compared to UV photons remains a major question.

CONCLUSIONS

New results based on analyses of 33 years of northern hemisphere meteorological data show clear correlations of winter cyclone intensity in mid-latitude oceanic regions with day-to-day changes in the cosmic ray flux, consistent with previously observed correlations on the time scale of the 11-year sunspot cycle. These point to a mechanism in which the MeV-GeV particle precipitation affects tropospheric thermodynamics, with a requirement for energy amplification by a factor of about 10^7 and a time scale of hours. A process is hypothesized in which ionization affects the nucleation and/or growth rate of ice crystals in high-level clouds, and thus changes the flux of ice crystals that can glaciate midlevel clouds. In warm core winter cyclones the consequent release of latent heat intensifies convection and extracts energy from the baroclinic instability to further intensify the cyclone. As a result, the general circulation in winter is affected in a way consistent with observed variations on the interannual/decadal time scale, although simultaneous effects resulting from UV flux changes have also been postulated. The effects of MeV-GeV particle precipitation on the concentration and size distribution of ice crystals and water droplets in high-level clouds may also influence circulation via radiative forcing.

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REFERENCES

Abbas, M. A., and J. Latham, The electrofreezing of supercooled water drops, *J. Meteorol. Soc. Jpn.*, *47*, 65, 1969.

Barth, C. A., W. K. Tobiska, G. J. Rottman, and O. R. White, Comparison of 10.7 radio flux with SME solar Lyman alpha flux, *Geophys. Res. Lett.*, *17*, 571, 1990.

Barlow, A. K., and J. Latham, A laboratory study of the scavenging of sub-micron aerosol by charged raindrops, *Quart. J. R. Meteorol. Soc.*, *109*, 763, 1983.

Brown, G. M., Short-term cosmic ray related changes in the troposphere, in *Workshop on Mechanism for Tropospheric Effects of Solar Variability and the Quasi-Biennial Oscillation*, edited by S. K. Avery and B. A. Tinsley, p. 24, Univ. of Colo., Boulder Colo., 1989.

Brown, G. M., and J. I. John, Solar cycle influences in tropospheric circulation, *J. Atmos. Terr. Phys.*, *41*, 43, 1979.

Dameris, M., and E. Ebel, The QBO and weak external forcing by solar activity: A three dimensional model study, in *Handbook for MAP*, *29*, 49, SCOSTEP Secretariat, University of Illinois, Urbana, 1989.

Dawson, G. A., and G. R. Cardell, Electrofreezing of supercooled water drops, *J. Geophys Res.*, *78*, 8864, 1973.

Dickinson, R. E., Solar variability and the lower atmosphere, *Bull. Am. Meteorol. Soc.*, *56*, 1240, 1975.

Donnelley, R. F., H. E. Hinteregger, and D. F. Heath, Temporal variations of solar EUV, UV, and 10830-A radiations, *J. Geophys. Res.*, *91*, 5567, 1986.

Doolittle, J. B., and G. Vali, Heterogenous freezing nucleation in electric fields, *J. Atmos. Sci.*, *32*, 375, 1975.

Eddy, J. A., Climate and the changing sun, *Climate Change*, *1*, 173, 1977.

Edwards, G. R., and L. F. Evans, Effect of surface charge on ice nucleation by silver iodide, *Trans. Faraday Soc.*, *58*, 1649, 1962.

Fleagle, R. G., and J. A. Businger, *An introduction to Atmospheric Physics*, 2nd ed., Academic, San Diego, Calif., 1980.

Gabarashvili, T. G., and N. V. Gliki, Origination of the ice phase in super cooled water under the influence of electrically charged crystals of cholesterol and naphthalene, *Izv. Atmos. Oceanic Phys.*, *3*, 570, 1967.

Geller, M. A., and J. C. Alpert, Planetary wave coupling between the troposphere and the middle atmosphere as a sun-weather mechanism, *J. Atmos. Sci.*, *37*, 1198, 1980.

Hamilton, W. C., E. P. Katsanis, and A. C. Zettlemoyer, An IR investigation of water adsorbed at different relative humidities on silicas of varying ice nucleation capabilities, in *Proceedings of 1st National Conference on Weather Modification*, p. 336, American Meteorological Society, Boston, Mass., 1968.

Herman, J. R., and R. A. Goldberg, Sun, Weather, and Climate, *NASA Spec. Publ.*, *NASA SP-426*, 1978*a*.

Herman, J. R., and R. A. Goldberg, Initiation of non-tropical thunderstorms by solar activity, *J. Atmos. Terr. Phys.*, *40*, 121, 1978*b*.

Herschel, W., Observations tending to investigate the nature of the sun, *Philos. Trans. R. Soc. London*, *Part 1*, 265, 1801.

Heymsfield, A. J., and R. M. Sabin, Cirrus crystal nucleation by homogeneous freezing of solution droplets, *J. Atmos. Sci.*, *46*, 2252, 1989.

Hinds, W. C., *Aerosol Technology*, John Wiley, New York, 1982.

Hobbs, P. V., *Ice Physics*, Clarendon, Oxford, 1971.

Hobbs, P. V., Holes in clouds, *Weatherwise*, *38*, 254, 1985.

Hobbs, P. V., and A. L. Rangno, Ice particle concentrations in clouds, *J. Atmos. Sci.*, *42*, 2523, 1985

Holman, D., Gallery, *Sky & Telescope*, *80*, 568, 1990.

Holton, J. A., Possible physical mechanisms: Dynamic coupling, in *Solar Variability, Weather and Climate*, p. 79, National Academy of Science Press, Washington, D. C., 1982.

Hood, L. L., and J. L. Jirikowic, A mechanism involving solar ultraviolet variations for modulating the interannual climatology of the middle atmosphere, *Climate Impact of Solar Variability*, *NASA Conf. Publ.*, *NASA CP3086*, 164, 1990.

Hoskins, B. J., Modelling the transient eddies and their feedback on the mean flow, in *Large Scale Dynamic Processes in the Atmosphere*, edited by B. J. Hoskins and R. Pearce, Academic, San Diego, Calif., 1983.

IZMIRAN, Cosmic ray intensity maximum in the stratosphere, in *Cosmic Data* (in Russian), Nauka, Moscow, 1972-1989.

John, J. I., Storm tracks and atmospheric circulation indices over the northeast Atlantic and northwest Europe in relation to the solar cycle and the QBO, in *Workshop on Mechanisms for Tropospheric Effects of Solar Variability and the Quasi-Biennial Oscillation*, edited by S. K. Avery and B. A. Tinsley, p. 209, Univ. of Colo., Boulder Colo., 1989.

John, J. I., Secular changes in storm tracks over the north Atlantic Ocean, 1920-89, (extended abstract), preprint volume, AMS Meeting, Anaheim, Calif., 1990.

Keating, G. M., M. C. Pitts, G. Brasseur and A. De Rudder, Response of middle atmosphere to short-term solar ultraviolet variations, 1, Observations, *J. Geophys. Res.*, *92*, 889, 1987.

Kodera, K., K. Yamazaki, M. Chiba, and K. Shibata, Downward propagation of upper stratospheric mean zonal wind perturbation to the troposphere, *Geophysical. Res. Lett.*, *17*, 1263, 1990.

Labitzke, K., Sunspots, the QBO and the stratospheric temperature in the north pole region, *Geophys. Res. Lett.*, *14*, 535, 1987.

Labitzke, K., and H. van Loon, Associations between the 11-year solar cycle, the QBO and the atmosphere, I, The troposphere and the stratosphere of the northern hemisphere in winter, *J. Atmos. Terr. Phys.*, *50*, 197, 1988.

Labitzke, K., and H. van Loon, Association between the 11-year solar cycle, the QBO, and the atmosphere, III, Aspects of the association, *J. Clim.*, *2*, 554, 1989.

Lean, J., Contribution of ultraviolet irradiance variations to changes in the sun's total irradiance, *Science*, *244*, 197, 1989.

Lebedev Institute, Cosmic ray intensity maximum in the stratosphere, data series, 1957-1971, *Acad. Sci. USSR*, 1968-1973.

Lethbridge, M. deV., Thunderstorms, cosmic rays, and solar-lunar influences, *J. Geophys. Res.*, *95*, 13645, 1990.

Loeb, L. B., A tentative explanation of the electrical field effect on the freezing of supercooled water drops, *J. Geophys Res.*, *68*, 4475, 1963.

Mason, B. J., *The Physics of Clouds*, 2nd ed., Clarendon, Oxford, 1971.

Märcz, F., Atmospheric electricity and the 11-year solar cycle associated with QBO, *Ann. Geophys.*, *8*, 525, 1990.

Markson, R., and M. Muir, Solar wind control of the Earth's electric field, *Science*, *206*, 979, 1980.

McDonald, N. J., and W. O. Roberts, Further evidence of a solar corpuscular influence on large scale circulation at 300 mb, *J. Geophys. Res.*, *65*, 529, 1960.

Mohnen, V. A., Stratospheric ion and aerosol chemistry and possible links with cloud microphysics—A critical assessment, in *Workshop on Mechanisms for Tropospheric Effects of Solar Variability and the Quasi-Biennial Oscillation*, edited by S. K. Avery and B. A. Tinsley, p. 75, Univ. of Colo., Boulder Colo., 1989.

Murphy, D. M., K. K. Kelly, A. F. Tuck, M. H. Proffitt and S. Kinne, Ice saturation at the tropopause observed from the ER-2 aircraft, *Geophys. Res. Lett.*, *17*, 353, 1990.

Neher, H. V., Cosmic rays at high latitudes and altitudes covering four solar maxima, *J. Geophys. Res.*, *76*, 1637, 1971.

Newkirk, G. A., The nature of solar variability, in *Solar Variability, Weather and Climate*, p. 33, National Academy of Science, Washington, D. C., 1982.

Ney, E. P., Cosmic radiation and the weather, *Nature, 183*, 451, 1959.

Nicolet, M., On the production of nitric oxide by cosmic rays in the mesosphere and stratosphere, *Planet. Space Sci.*, *23*, 637, 1975.

National Geophysical Data Center (NGDC), Forbush decreases 1955-1984, in *Solar Geophysical Data*, no. 485, part 1, p. 91., National Geophysical Data Center, National Oceanic and Atmospheric Administration, Boulder, Colo., 1985.

NGDC01, *Solar Geophysical Data on CD ROM* (optical disc), National Geophysical Data Center, National Oceanic and Atmospheric Administration, Boulder, Colo., 1987.

NGDC, *Cosmic Ray Hourly Count Rates 1953-1987* (magnetic tape), National Geophysical Data Center, National Oceanic and Atmospheric Administration, Boulder, Colo., 1989.

National Research Council Panel on Solar Variability, Weather, and Climate, *Solar Variability, Weather and Climate*, National Academy of Science, Washington, D. C., 1982.

Olsen, R. H., W. O. Roberts, and C. S. Zerefos, Short term relationships between solar flares, geomagnetic storms, and tropospheric vorticity patterns, *Nature*, *257*, 113, 1975.

Pauley, P. M., and P. J. Smith, Direct and indirect effects of latent heat release on a synoptic scale wave system, *Mon. Weather Rev.*, *116*, 1209, 1988.

Phillips, J. D., Gallery, *Sky & Telescope*, *80*, 216, 1990.

Pittock, A. B., A critical look at long term sun-weather relationships, *Rev. Geophys. Space. Phys.*, *16*, 400, 1978.

Pruppacher, H. R., The effect of an external electric field on the supercooling of water drops, *J. Geophys. Res.*, *68*, 4463, 1963.

Pruppacher, H. R., Electrofreezing of super cooled water, *Pure Appl. Geophys.*, *104*, 623, 1973.

Rauber, R. M., and A. Tokay, An explanation for the existence of supercooled water at the tops of clouds, *J. Atmos. Sci.*, *48*, 1005, 1991.

Reid, G. C., Solar activity and the sea surface temperature record—Evidence of a long-period variation in solar total irradiance? Climate Impact of Solar Variability, *NASA Conf. Publ.*, *NASA CP3086*, 1990.

Roberts, W. O., and R. H. Olson, Geomagnetic storms and wintertime 300 mb trough development in the North Pacific-North America area, *J. Atmos. Sci.*, *30*, 135, 1973.

Roble, R. C., and P. B. Hays, Solar-terrestrial effects on the global electric circuit, in *Solar Variability, Weather and Climate*, p. 92, National Academy of Science, Washington, D. C., 1982.

Rosen, J. M., and D. J. Hofmann, A search for large ions in the stratosphere, *J. Geophys. Res.*, *93*, 8415, 1988.

Rutledge, S. A., and P. V. Hobbs, The mesoscale and microscale structure and organization of clouds and precipitation in midlatitude cyclones, VIII, A model for the "Seeder Feeder" process in warm-frontal rainbands, *J. Atmos. Sci.*, *40*, 1185, 1983.

Sassen, K., and G. C. Dodd, Homogeneous nucleation rate for highly supercooled cirrus cloud droplets, *J. Atmos. Sci.*, *45*, 1357, 1988.

Schatten, K. H., A model for solar constant secular changes, *Geophys. Res. Lett.*, *15*, 121, 1988.

Schuurmans, C. J. E., and A. H. Oort, A statistical study of pressure changes in the troposphere and lower stratosphere after strong solar flares, *Pure Appl. Geophys.*, *75*, 233, 1969.

SCOSTEP, Solar-terrestrial physics and meteorology, *Work. Doc. I, II, and III*, World Data Cent. A, Natl. Oceanic and Atmos. Admin., Boulder, Colo., 1975, 1977, and 1979.

Stolov, H. L., and R. Shapiro, Investigation of the responses of the general circulation at 700 mb to solar geomagnetic disturbance, *J. Geophys. Res.*, *29*, 2161, 1974.

Taylor, H. A., Selective factors in sun-weather research, *Rev. Geophys.*, *24*, 329, 1986.

Tinsley, B. A., The solar cycle and the QBO influences on the latitude of storm tracks in the North Atlantic, *Geophys. Res. Lett.*, *15*, 409, 1988.

Tinsley, B. A., Forcing of climate variations by MeV-GeV particles?, *Climate Impact of Solar Variability*, *NASA Conf. Publ.*, *NASA CP-3086*, edited by K. H. Schatten and A. Arking, 249, 1990*a*.

Tinsley, B. A., Forcing of the troposphere and stratosphere by MeV-GeV particle flux variations: Observations and a new cloud microphysical mechanism (abstract), *EoS Trans. AGU*, *71*, 1250, 1990*b*.

Tinsley, B. A. Interpretation of short-term solar variability effects in the troposphere, Proceedings of 7th Quadrennial Solar-Terrestrial Physics Symposium, edited by K. Cole, et al., in press, *Special issue of J. Geomag. Geoelect.*, 1991.

Tinsley, B. A., G. M. Brown and P. H. Scherrer, Solar variability influences on weather and climate; possible connections through cosmic ray fluxes and storm intensification, *J. Geophys. Res.*, *94*, 14783, 1989.

Twomey, S., *Atmospheric Aerosols*, Elsevier, New York, 1977.

van Delden, A., Gradient wind adjustment, CISK, and the growth of polar lows by diabatic heating, in *Polar and Arctic Lows*, edited by P. F. Twitchell, et al., p. 109, Deepack, Hampton, Va., 1989*a*.

van Delden, A., On the deepening and filling of balanced cyclones by diabatic heating, *Meteorol. Atmos. Phys.*, *41*, 127, 1989*b*.

van Loon, H., and K. Labitzke, Association between the 11 year solar cycle, the QBO, and the atmosphere, Part III, surface and 700 mb on the northern hemisphere in winter, *J. Clim.*, *1*, 905, 1988.

Varotsos, C., Comment on connection between the 11-year solar cycle, the Q.B.O. and total ozone, *J. Atmos. Terr. Phys.*, *51*, 367, 1989.

Varshneya, N. C., Detecting radiation with a supercooled liquid, *Nature*, *223*, 826, 1969.

Varshneya, N. C., Theory of radiation detection through supercooled liquid, *Nuclear Inst. Methods*, *92*, 147, 1971.

Venne, D. E., and D. G. Dartt, An examination of possible solar-cycle QBO effects in the northern hemisphere troposphere, *J. Climate*, *3*, 272, 1990.

Wallace, J. M. and P. V. Hobbs, *Atmospheric Science, An Introductory Survey*, Academic, San Diego, Calif., 1977.

Wang, P. K., S. N. Grover and H. R. Pruppacher, On the effect of electric charges on the scavenging of aerosol particles by clouds and small raindrops, *J. Atmos. Sci.*, *35*, 1735, 1978.

Wigley, T. M. L., and S. C. B. Raper, Climate change due to solar irradiance changes, *Geophys. Res. Lett.*, *17*, 2169, 1990.

Wilcox, J. M., P. H. Scherrer, L. Svalgaard, W. O. Roberts, and R. H. Olson, Solar magnetic structure: Influence on stratospheric circulation, *Science*, *180*, 185, 1973.

Wilcox, J. M., P. H. Scherrer, L. Svalgaard, W. O. Roberts, R. H. Olson, and R. L. Jenne, Influence of solar magnetic structure on terrestrial atmospheric vorticity, *J. Atmos. Sci.*, *31*, 581, 1974.

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